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MEMORANDUM

TO: Robert C. Hendricks
NASA Lewis Research Center
M.S. SPTD-3

FROM: Dara W. Childs
Director, Turbomachinery Laboratory
M.S. 3254

Dara Childs

SUBJECT: Final Report for NASA Grant NAG 3-181 (RF 4502-0)

This memorandum with its accompanying enclosures is the final report for Grant NAG 3-181, which started on June 1, 1981 and ended on November 30, 1994. Two principal investigators were involved: Dara W. Childs and Gerald Morrison. Morrison's work concerned laser measurements of velocity fields in annular seals, and his final report is submitted separately.

Introduction and Program Summary

The research program involved the development and verification of models for forces developed by annular gas seals and their influence on the vibration characteristics of high-performance turbomachinery. The linear reaction-force model for annular seals is

$$-\begin{Bmatrix} F_X \\ F_Y \end{Bmatrix} = \begin{bmatrix} K_{XX} & K_{XY} \\ K_{YX} & K_{YY} \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} + \begin{bmatrix} C_{XX} & C_{XY} \\ C_{YX} & C_{YY} \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} \tag{1}$$

where (F_X, F_Y) are components of the reaction-force vector, and (X, Y) are components of the displacement vector for small motion about a static eccentricity vector defined by ε_o. The stiffness and damping coefficients are functions of ε_o. For small motion about a centered

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where (F_X , F_Y) are components of the reaction-force vector, and (X, Y) are components of the displacement vector for small motion about a static eccentricity vector defined by ε_0. The stiffness and damping coefficients are functions of ε_0. For small motion about a centered position, the model of Eq.(1) reduces to

$$-\begin{Bmatrix} F_X \\ F_Y \end{Bmatrix} = \begin{bmatrix} K & k \\ -k & K \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} + \begin{bmatrix} C & c \\ -c & C \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} \tag{2}$$

At the outset of this program, there were stiffness test data for long labyrinth seals and one honeycomb configuration from Benckert and Wachter (1978, 1979, 1980a, 1980b). Wright (1983) had performed tests on a single-cavity labyrinth seal to provide estimates of damping. However, there were generally no data available for damping, and Benckert and Wachter's stiffness data for seals treated preswirl and shaft rotation separately.

On the analysis side, Iwatsubo (1980) and Iwatsubo et al. (1982) published the first one-control-volume model for labyrinth seals. Fleming (1979, 1980) published the first analysis for smooth annular seals; however, his analyses were one dimensional, neglecting circumferential flow in the seals.

By virtue of the research conducted under grant NAG 3-181, very significant advances have been made in both the understanding of annular seals and the ability to predict their dynamic characteristics. A summary of research accomplishments is listed below:

(1) Useful validated analyses have been developed for see-through labyrinth seals. Childs and Scharrer (1986) and Scharrer (1987) have presented one-control-volume and two-control-volume models for labyrinth gas seals which have become the standard tools for estimating rotordynamic coefficients for labyrinth seals in the U.S.

(2) Analyses have evolved for plain annular seals (smooth, stepped, honeycomb) at Texas A&M University (TAMU) through the work of Nelson (1984, 1985), Dunn (1990), Elrod et al. (1989, 1990), Ha and Childs (1994). At present, reasonable analyses are available for smooth seals with constant-clearance, tapered, and step geometries. As will be discussed further below, additional work is needed for honeycomb seals.

(3) A test apparatus was developed and used to measure stiffness and damping coefficients for numerous seal configurations for a wide range of supply pressures, running speeds, preswirl ratios, and pressure ratios. Tests were conducted for the following seal configuration:

    (a) Tooth-on-stator labyrinths
    (b) Tooth-on-rotor labyrinths, smooth stators
    (c) Tooth-on-rotor labyrinths, honeycomb stator

(d) Interlocking seals
(e) Brush seals (4, 5, and 6 stages)
(f) Smooth seals, constant clearance
(g) Smooth seals, taper geometries
(h) Smooth seals, step configuration
(i) Honeycomb seals
(j) Helically-grooved stator/smooth-rotor seals

Most of the seals were tested in the centered position; however, a smooth, constant-clearance seal was tested for a range of eccentricity ratios, Alexander et al. (1994). At least 95% of the published data for dynamic coefficients of annular gas seals available in the world today was generated under grant NAG 3-181. The data will continue to serve as a validation test for analysis codes which are developed to predict rotordynamic coefficients.

Concerning honeycomb-stator/smooth-rotor seals, tests within this program first demonstrated the remarkable advantages inherent in the use of honeycomb as compared to see-through or interlocking labyrinth seals. The early German tests by Wachter and Benckert had shown that the cross-coupled stiffness coefficients for honeycomb were larger than labyrinths, suggesting that honeycomb should be avoided. However, tests at TAMU which included damping showed the opposite; namely, because of large damping, long honeycomb seals are much better than labyrinth seals. They also leak less. Acceptance of honeycomb seals by the commercial turbomachinery community was slow for many years. However, recent "success-story" publications by Zeidan et al. (1993) and Sorokes et al. (1994) have stimulated an accelerating acceptance of honeycomb. Aggressive marketing by RSR and KMC is also helping in the replacement of labyrinths by honeycomb in centrifugal compressors and steam turbines.

With regard to brush seals, the data developed at TAMU show that replacing labyrinths with brush seals will generally improve rotordynamics of aircraft gas turbines. The main reason for the accelerated use of brush seals in aircraft gas turbines is performance improvement; however, the TAMU data have made a modest and continuing contribution to the accelerated use of this technology.

Tests of see-through annular seals showed that teeth-on-stator configurations are slightly more stable than teeth-on-rotor configurations, Childs and Scharrer (1986). Hawkins et al. (1988) demonstrated that the rotordynamic characteristics of tooth-on-rotor seals with smooth and honeycomb stators were comparable. Tests of interlocking seals showed a substantial reduction in direct damping, Childs et al. (1988).

Gansle's tests of helically-grooved-stator/smooth-rotor seals showed that a negative cross-coupled stiffness could be developed, which would oppose forward whirl. At present, no analysis is available for turbulent flow for this type of seal, which would permit design optimization. Commercial applications remain to be seen.

Concerning swirl brakes, tests were conducted which showed that a redesign could be implemented in the SSME-HPOTP turbine interstage seal which would reduce cross-coupled stiffness by a factor of two. Tests also confirmed the remarkable effectiveness of the Pratt and Whitney swirl-brake design for the ATD-HPFTP turbine interstage.

Publications

Twenty three journal and conference papers have been published as a result of this grant, and twenty contract test reports have been published. The paper by Childs et al. (1986) was recognized as the best paper published by the ASME Journal of Tribology in 1986. A listing of all papers and reports is given in Appendix A.

Graduate Education

Funds from this program have helped provide graduate education support for a number of students, leading to 3 Ph.D. and 10 M.S. Degrees. Most of these graduates continue to practice engineering in the field of turbomachinery. Two of the Ph.D. holders (Elrod and Ha) are teaching in engineering colleges. Scharrer has started his own company for research and development in rotordynamics and seals. A listing of graduate degrees granted is provided in Appendix B.

Continuing Education

Funds from grant NAG 3-181 have been used to partially support a series of workshops at TAMU on, "Rotordynamic Instability Problems in High Performance Turbomachinery". NASA has published the proceedings of these workshops as a CP series. The workshops and proceedings have made a singular contribution to eliminating and controlling instability problems in both commercial and aerospace turbomachinery. Appendix C provides a listing of workshop proceedings. Additional eccentric testing is needed for other seal geometries.

Closure

Not all of the problems in annular gas seals have been solved, and many questions remain unanswered. Most of the data developed in this study were for centered seals; only one test series was carried out for an eccentric seal. Those tests showed a smooth, constant-clearance seal to be more sensitive to eccentricity than predicted.

The ability to predict the dynamic characteristics of honeycomb seals continues to be disappointing. Ha et al. (1992) showed via friction-factor data and transient pressure measurements that honeycomb can display strong acoustic phenomena, which partially explains the difficulty involved in predicting honeycomb-seal characteristics. A test program is currently under way at TAMU to measure friction factors due to shear-driven flow. We hope that these data will support a new model with improved accuracy in predicting damping and cross-coupled stiffness coefficients.

An industrially supported program is also under way to determine if "hole-pattern" seals can be made from high-strength plastics using numerically-controlled machinery that match the performance of honeycomb. Such "manufactured", hole-pattern seals would be more confidently used by commercial-machinery users, since the possibility of shaft damage due to rub would be eliminated. Industrial support is also being used to test additional interlocking seals which are representative of industrial gas turbines and centrifugal compressors.

References

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APPENDIX A: PUBLICATIONS

Journal and Conference Papers

Alexander, C., Childs, D., and Yang, Z., "Theory versus Experiment for the Rotordynamic Characteristics of a Smooth Gas Annular Seal at Eccentric Positions," presented at the ASME/STLE Tribology Conference, Hawaii, October 16-19, 1994 and accepted for publication in the *ASME Trans., Journal of Tribology.*

Childs, D. and Kleynhans, G., "Theory Versus Experiment for Short (L/D=1/6) Honeycomb and Smooth Annular Pressure Seals," proceedings *14th ASME Vibration and Noise Conference*, September 19-22, 1993, Albuquerque, NM.

Childs, D. and Kleynhans G., "Experimental Rotordynamic and Leakage Results for Short (L/D = 1/6) Honeycomb and Smooth Annular Pressure Seals,'' proceedings, Fifth International Conference on Vibrations in Rotating Machinery, September 7-10, 1992, Bath, England.

Childs, D. W., Baskharone, E. A. and Ramsey, C., "Test Results for Rotordynamic Coefficients of the SSME HPOTP Turbine Interstage Seal With Two Swirl Brakes,'' *ASME Trans., Journal of Tribology,* July 1991, Vol. 113, pp.577-583.

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Childs, D., Elrod, D., and Hale, K., "Rotordynamic Coefficient and Leakage Test Results for Interlock and Tooth-on-Stator Labyrinth Seals,'' ASME Paper No. 88-G7-87, ASME International Gas Turbine Conference, Amsterdam, The Netherlands, June 1988.

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Conner, K. and Childs, D., "Rotordynamic Coefficient Test Results For A 4-Stage Brush Seal," *AIAA Journal of Propulsion and Power,* June 1993, pp. 462-465.

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Test Reports

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient Results For A 5-Stage Brush Seal," TRC-SEAL-7-92, (#353).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient Results For A 6-Stage Brush Seal," TRC-SEAL-8-92, (#354).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.005, C_h = 2.29mm, and C_w = 0.79mm," TL-SEAL-9-92, (#355).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.004, C_h = 2.29mm, and C_w = 0.79mm," TL-SEAL-10-92, (#356).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.004, C_h = 2.29mm, and C_w = 0.40mm," TL-SEAL-11-92, (#357).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.005, C_h = 2.29mm, and C_w = 0.40mm," TL-SEAL-12-92, (#358).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.003, C_h = 2.29mm, and C_w = 0.79mm," TL-SEAL-13-92, (#359).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Honeycomb Seal With L/D =1/3, C_r = 0.003, C_h = 2.29mm, and C_w = 0.40mm," TL-SEAL-14-92, (#360).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Smooth Seal With L/D =1/3, C_r = 0.004," TL-SEAL-15-92, (#361).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient And Static Characteristic Results for a Smooth Seal With L/D =1/3, C_r = 0.003," TL-SEAL-16-92, (#362).

M. Griffin, G. Kleynhans, C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient Results For A 4-Stage Brush Seal," TL-SEAL-17-92, (#363).

M. Griffin, T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient and Static Characteristic Results for a Circumferentially Grooved Seal with L/D = 1/3 and C_r /R = 0.004,'' TL-SEAL-18-92, (#364).

C. Alexander T. Pierce, and D. Childs,"Experimental Rotordynamic Coefficient and Static Characteristic Results for a Circumferentially Grooved Seal with L/D = 1/3 and C_r /R = 0.003,'' TL-SEAL-19-92, (#365).

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Childs, D. W., "Testing of Brush Seals,'' TRC-Seal-5-92, (#351).

Childs, D. W., "Improved Rotordynamic-Analysis Model for Labyrinth Seals,'' TRC-SEAL-6-92, (#351).

Dunn, M., "A Comparison of Experimental Results and Theoretical Predictions for the Rotordynamic Coefficients of Stepped Annular Gas Seals" TL-SEAL-3-90, (#341).

Childs, D. W., Ramsey, C. J., "Test Results For Interlocking Labyrinth and Amoco Honeycomb-Stator/Labyrinth-Rotor Air Seal,'' Turbomachinery Laboratories Report, TRC-Seal-2-89, (#337).

Elrod, D. A. and Childs, D. W., "Experimental Rotordynamic Coefficient Results for Honeycomb Seals,'' Turbomachinery Laboratories Report, TL-Seal-1-88,(#330).

Childs, D. W., Elrod, D. A., and Hale, K., "Experimental Rotordynamic Coefficient Results for Interlocking Labyrinth Gas Seal,'' Turbomachinery Laboratories Report, TRC-Seal-6-87, (#328).

APPENDIX B:

GRADUATE-STUDENT PRODUCTION

Student Name	Ph.D. Eng.	MS Eng.	Date Grad
C. Alexander		X	08/93

Thesis Title: "A Comparison of the Theoretical and Experimental Rotordynamic Coefficients for a Smooth Gas Seal at Eccentric Operation"

A. Gansle		X	12/93

Thesis Title: A Comparison of Theoretical and Experimental Rotordynamic Coefficients for Helically Grooved Annular Gas Seals

T. Ha	X		12/92

Thesis Title: "Rotordynamic Analysis of Annular Honeycomb-Stator Turbulent Gas Seals Using a New Friction-Factor Model Based on Flat Plate Tests"

T. Ha		X	05/89

Thesis Title: "Friction-Factor Data for Flat Plate Tests of Smooth and Honeycomb Surfaces"

G. Kleynhans		X	12/91

Thesis Title: "A Comparison of Experimental Results and Theoretical Predictions for the Rotordynamic and Leakage Characteristics of Short (L/D=1/6) Honeycomb and Smooth Annular Pressure Seals"

K. Conner		X	12/90

Thesis Title: "Rotordynamic and Leakage Characteristics of a 4-Stage Brush Seal"

M. Dunn		X	12/90

Thesis Title: "A Comparison of Experimental Results and Theoretical Predictions for the Rotordynamic Coefficients of Stepped Annular Gas Seals"

L. Hawkins		X	05/88

Thesis Title: "A Comparison of Experimental and Theoretical Results for Labyrinth Gas Seals with Honeycomb Stators"

J. Scharrer	X		05/87

Thesis Title: "A Comparison of Experimental and Theoretical Results for Labyrinth Gas Seals"

J. Scharrer		X	05/85

Thesis Title: "A Comparison of Experimental and Theoretical Results for Rotordynamic Coefficients for Labyrinth Gas Seals"

C. Nicks X 12/84

Thesis Title: "A Comparison of Experimental and Theoretical Results for Leakage, Pressure Distribution, and Rotordynamic Coefficients for Annular Gas Seals"

D. Elrod X 08/88

Thesis Title: "Entrance and Exit Region Friction Factor Models for Annular Seal Analysis"

D. Elrod X 12/86

Thesis Title: "A Comparison of Experimental and Theoretical Results for Leakage, Pressure Gradient, and Rotordynamics Coefficients for Tapered Annular Gas Seal"

G. Kleynhans X In Progress

M. Griffin X In Progress

ZePing Yu X In Progress

APPENDIX C:

INSTABILITY WORKSHOP PROCEEDINGS

Rotordynamic Instability Problems in High-Performance Turbomachinery-1993, NASA CP3239, Proceedings of a Workshop held at Texas A&M University, College Station, Texas, 10-12 May 1993; co-editors: Dara Childs and Robert C. Hendricks, published January 1994.

Rotordynamic Instability Problems in High-Performance Turbomachinery-1990, NASA CP3122, Proceedings of a Workshop held at Texas A&M University, College Station, Texas, 21-23 May 1990; co-editors: Jørgen L. Nikologsen and Robert C. Hendricks, published October 1991.

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Rotordynamic Instability Problems in High-Performance Turbomachinery-1986, NASA CP2443, Proceedings of a Workshop held at Texas A&M University, College Station, Texas, 2-4 June 1986; co-editors: Dara Childs, Robert C. Hendricks, and John Vance, published June 1987.

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